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LOW REYNOLDS NUMBER TURBINE BLADE CASCADE CALCULATIONS

Richard Rivir
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1996

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Low Reynolds NumberTurbine Blade Cascade Calculations

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ABSTRACT

Computations of the velocity fields for Langston turbine blade cascades with solidities of 1.075 and 0.84 have been carried out at Reynolds numbers of 50K, 100K, 200K, 441K, 1000K, and 2000K. A second cascade investigated at Reynolds numbers of 50K and 100K uses the Langston airfoil which has been modified by extending the trailing edge, resulting in a solidity of 0.786. The computations were performed with Allison's Blade Vane Interaction code. Computational results are presented for transition, separation and reattachment.

Keywords: Turbine, Low Reynolds Number, Transition, Separation, Reattachment

1. INTRODUCTION

It is suspected that the inability to accurately predict the transition, separation, and reattachment at the low Reynolds numbers is associated with the high levels of turbulence and unsteadiness of the flow. A low pressure turbine typically operates at a chord Reynolds number of 10^6 at take off. This chord Reynolds number falls to 150,000 to 50,000 at altitude in a number of engines. Modern turbine blades have high aft loading so unpredicted transition, transition length and separations cause significant losses. C-17(F-117) engines as well as smaller engines with their associated smaller blades typically exhibit higher than predicted SFC during high altitude operation. Sharma[8] reported a near doubling of the measured loss coefficient when the chord Reynolds number is reduced from 300K to 50K with an additional operational loss of 0.8% in SFC over design calculations. Halstead et al., [5] have recently conducted an extensive experimental and computational investigation of low Reynolds number effects on both compressor and turbine blades. On the low pressure turbine blades which they investigated the wake induced turbulent transition region was coupled to the non wake region by an unusual calmed region. Existing codes which they investigated were unable to accurately describe the flows. The Allison Turbine Vane-Blade Interaction (VBI) code to be used in this study has demonstrated a modeling of the wakes interaction with the rotor and is a potentially useful code for this problem. This is the first phase of this study and results with out wakes for only a stationary rotor will be presented at this time.

2. COMPUTATIONAL RESULTS

The Langston cascade [6] was chosen as the geometry for investigation since it is a well documented geometry at higher Reynolds numbers, while still fairly representative of current low pressure turbine geometries. Experimental suction surface heat transfer coefficients have recently been obtained by Baughn et al.,[2] for the Langston cascade at low Reynolds numbers. The computational code used for the numerical simulation of the steady Navier-Stokes equations was the VBI code developed by the Allison engine company, Rao et al., [7] under U.S. Air Force contract. The grid used in this code is an

overlaid combination of a rectangular H grid and a body fitted hyperbolic O grid as shown in Figure 1. The rectangular grid is used to resolve the free stream flow and the O grid is used to resolve the regions of high shear associated with the boundary layer. Small values of y+ have been employed in the calculation for the O grid spacing, with the first grid point at a y+ of 1 or less. The steady state solution of the code is based on a five step Runge Kutta relaxation method that incorporates residual smoothing to accelerate convergence to the final solution. The code implements a Baldwin-Lomax [1] two-layer algebraic turbulence model and the Baldwin-Lomax point transition model. Transition occurs at the fixed recommended value of the turbulent coefficient of viscosity, c_μ=14. Steady state residuals for these calculations are typically the order of 10^{-6}.

3. RESULTS AND DISCUSSION

The calculations were performed for the Langston cascade at chord Reynolds numbers of 50K, 100K, 200K, 441K, 1000K, and 2000K. Calculations for two solidities, or chord to pitch ratios, 1.075 (original Langston spacing) and 0.84, were investigated for all six Reynolds numbers. The locations of transition, separation, and reattachment are measured from the tangent to the leading edge and projected onto the x axis. This convention was also employed by Baughn et al., [1], in a linear Langston cascade, and Dring et al., [4], Blair et al., [2], and [3], in a large low speed steady state rotating Langston cascade.

The choice of the tangent to the leading edge to measure the location of transition, separation and reattachment may mask another effect. A small separation bubble was observed near the stagnation point that can alter the surface path length to the event (transition, separation, or reattachment) by up to 8% of the chord. This leading edge separation bubble is however not present for the Reynolds number of 50K.

Grid independence was investigated thoroughly for the original applications of the code. This investigation was conducted at the lowest applicable Mach number of the code and grid independence has been rechecked for this application. The results of the grid independence study are shown in Figures 2 and 3 by comparing the calculated pressure distributions and skin friction coefficients for three grids (66x25 H, 99x15 O), (99x51 H, 99x29 O), (99x99 H, 99x59 O). The pressure distributions of Figure 2 clearly indicate grid independence for the last two grids while the skin friction coefficient, a very sensitive indication of grid independence, very nearly indicates independence as the intermediate grid spacing is doubled in Figure 3. The standard grid spacing for the computations to be presented will be 99x51 for the H grid and 99x29 for the O grid.

4. EFFECTS OF REYNOLDS NUMBER AND SOLIDITY

Figures 4 through 7 present the results for cascade solidities (C/p) of 1.075. Figure 4 shows the skin friction distribution for a Reynolds number of 50K for the original Langston spacing, indicating separation at (x/C=0.63) and reattachment at (x/C=0.83). At a Reynolds number of 100K the skin friction coefficient oscillates in Figure 5 as the laminar flow tries to separate the turbulence model turns on keeping the flow attached. The oscillation in the skin friction coeficient disappear after a Reynolds number of 200K with the distributions approaching the high Reynolds number, 2000K, solution shown in Figure 6.

Figures 7 through 10 present the results for the 0.84 solidity cascade. The skin friction coefficient for the Reynolds number of 50K is shown in Figure 7, there are large changes in slope of the skin friction distribution before separation, then the zero crossing at separation, (x/C=0.66), and no reattachment. At a Reynolds number of 100K transition has occured at x/C=0.0213, separation at 0.6, and reattachment at 0.87 as illustrated in Figure 8. The separation, for the low solidity case, C/p=0.84, continues to move forward until it stabilizes at an x/C of 0.57-0.6 and reattachment settling out at 0.8 after a Reynolds number of 200K. The vector velocity field for a Reynolds number of 441K is shown in Figure 9, with separation at 0.6 and reattachment at 0.8.

The distribution of the separation and reattachment location in % of x projected cord is shown in Figures 10 and 11 for both solidities. After a Reynolds number of 100K there is effectively no separation in this cascade for the solidity of 1.075 while the C/p=0.84 case remains separated for all

Reynolds numbers. The indicated transition location is shown in Figure 12 for both solidity ratios. The transition location moves forward as the Reynolds number is increased with the entire blade effectively turbulent after a Reynolds number of 441K for c/p=1.075. Transition has effectively occurred by a Reynolds number of 100K for C/p=0.84 as indicated in Figure 12.

The Langston airfoil was modified by extending the trailing edge until the radius of the trailing edge was reduced by 0.25 of that of the original blade. Extending the blade also results in a further reduction in solidity to c/p=0.7857. The separation occurs at x/C=.515 and reattachment occurs at x/C=0.938 for the 50K Reynolds number. The resulting blade profile is indicated by the outline of the vector velocity field in Figure 13 for the Reynolds number of 50K. The skin friction coefficient at a Reynolds number of 100K is presented in Figure 14. A small separation bubble occurs at x/C=0.515, then reattaches immediately at 0.607. The improvement resulting from the sharp trailing edge blade may be seen by comparing Figure 14 with Figure 8 which shows no reattachment at 100K. however the aft loading has not returned.

5. SUMMARY

The presented results demonstrated the sensitivity of separation, and reattachment to Reynolds number and solidity for the range of Reynolds numbers of 50K to 2000K. The Langston profile with a pitch to chord spacing of 1.18 showed separation for all values of Reynolds numbers investigated in this study. The Langston profile with a pitch to chord spacing of 0.93, the original Langston spacing, showed separation at a Reynolds number of 50K, oscillating transition at 100K and attached flow for all other Reynolds numbers. A fixed value of c_μ was used in the calculations. Transition location for the Reynolds number range of 50K to 2000K was presented. Sharpening the trailing edge and covering the suction surface provided a simple cure for the separation but did not return the high aft loading obtained at high Reynolds numbers.

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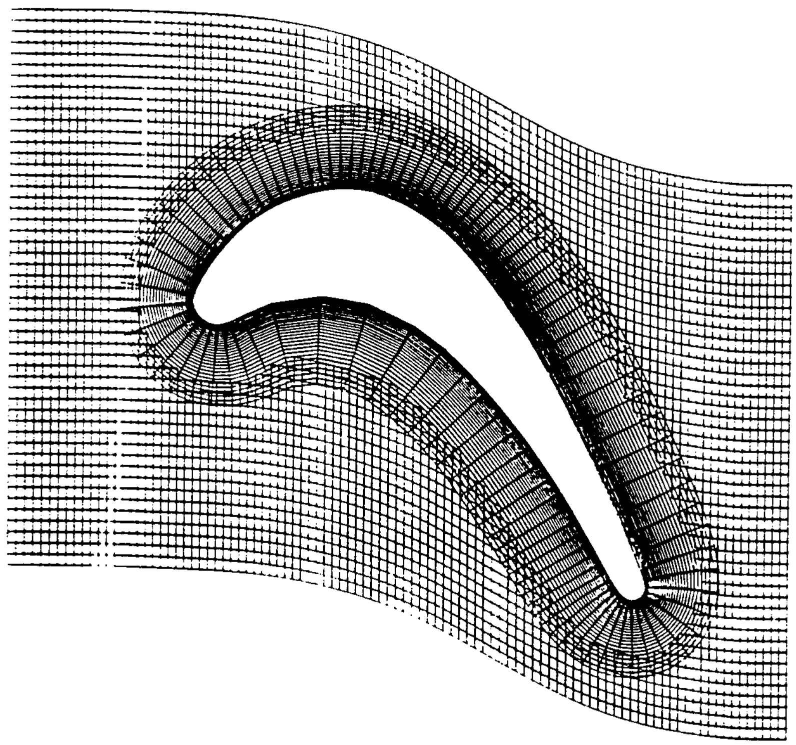

Figure 1. Overlaid H and O Grids, H:99x51,O: 99x29

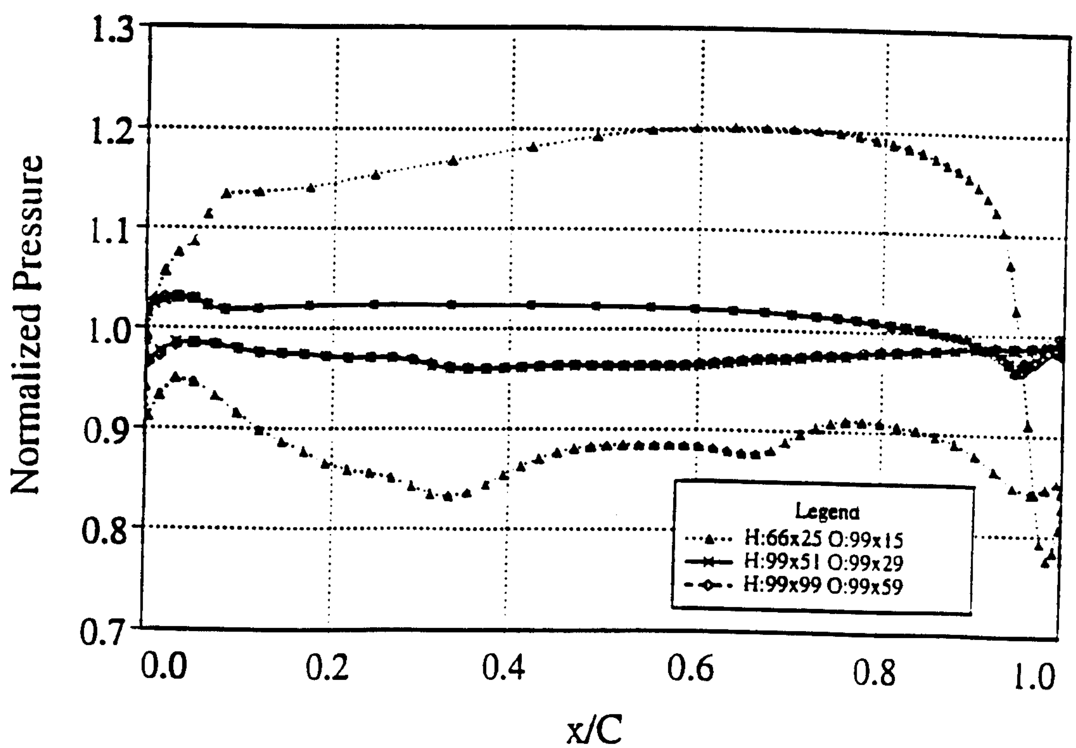

Figure 2. VBI Blade Pressure Coefficient / Grid Independence Comparison

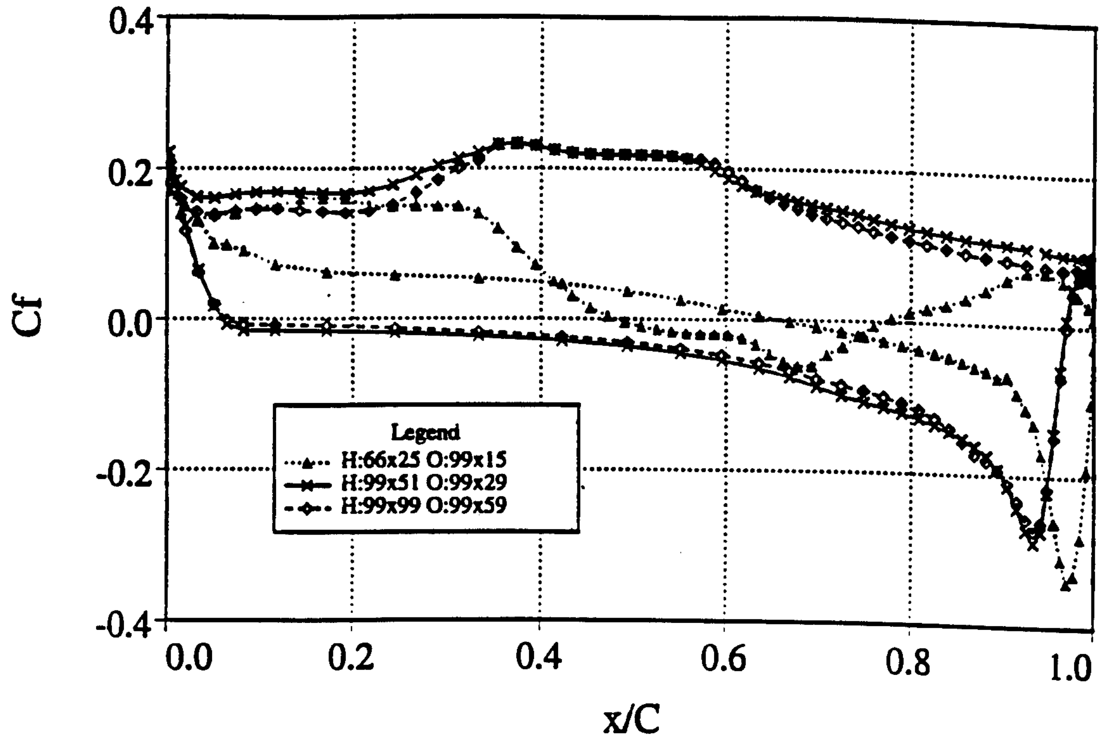

Figure 3. Grid Independence/Resolution, Chord R_e =441K, H Grid =99x51, O Grid=99x29, Chord/Pitch=0.84

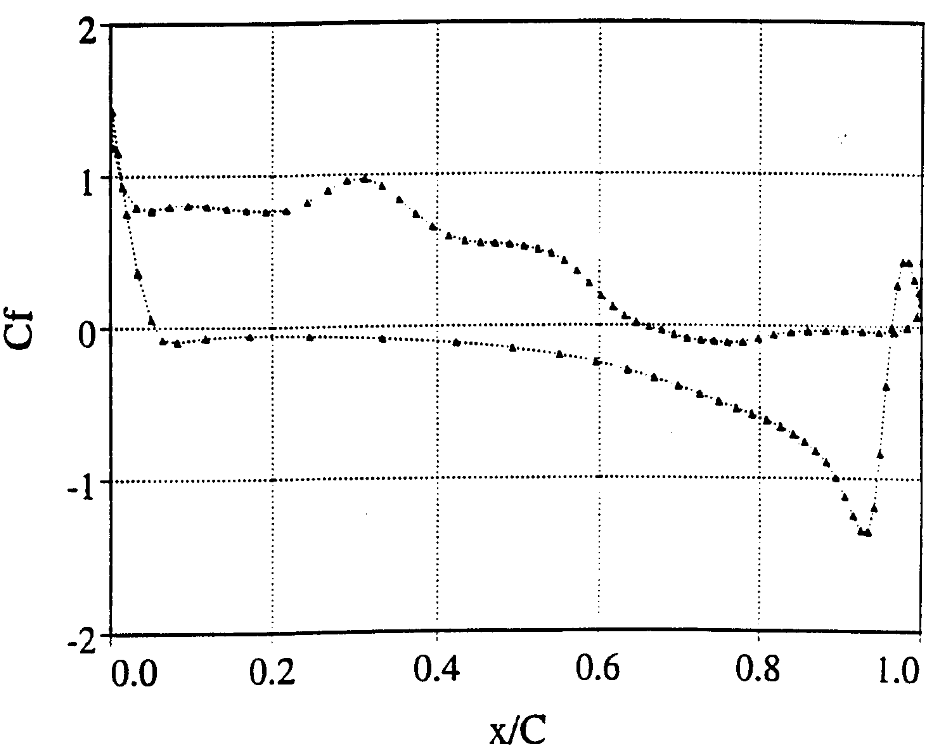

Figure 4. Skin Friction Distribution, Chord R_e =50K, H Grid =99x51, O Grid=99x29, Chord/Pitch=1.075

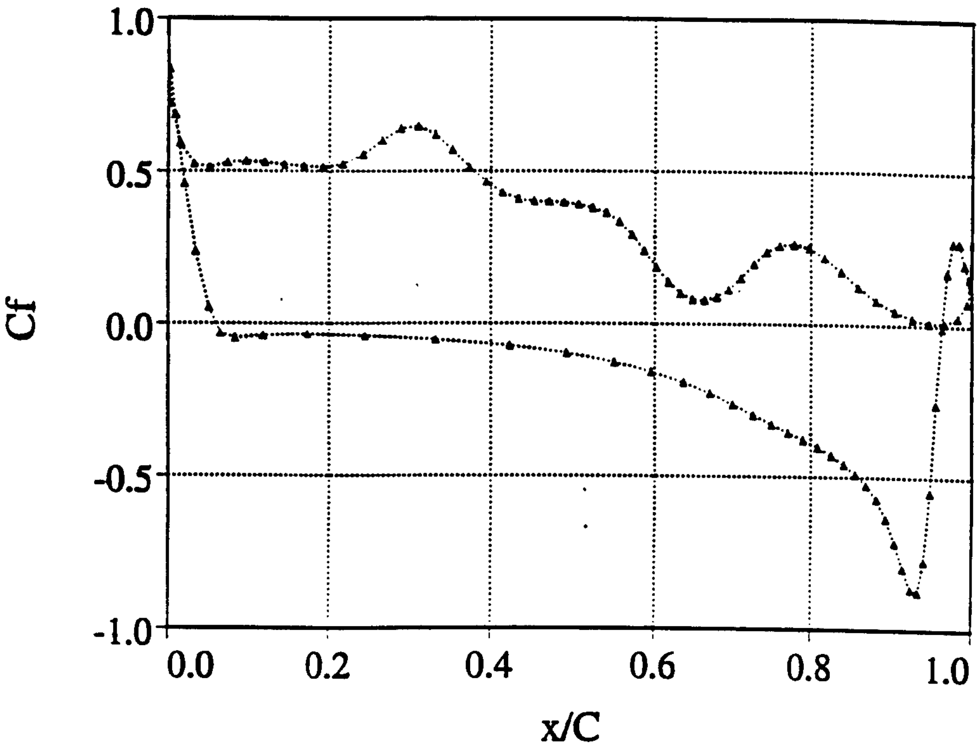

Figure 5. Skin Friction Distribution, Chord R_e =100K, H Grid =99x51, O Grid=99x29, Chord/Pitch=1.075

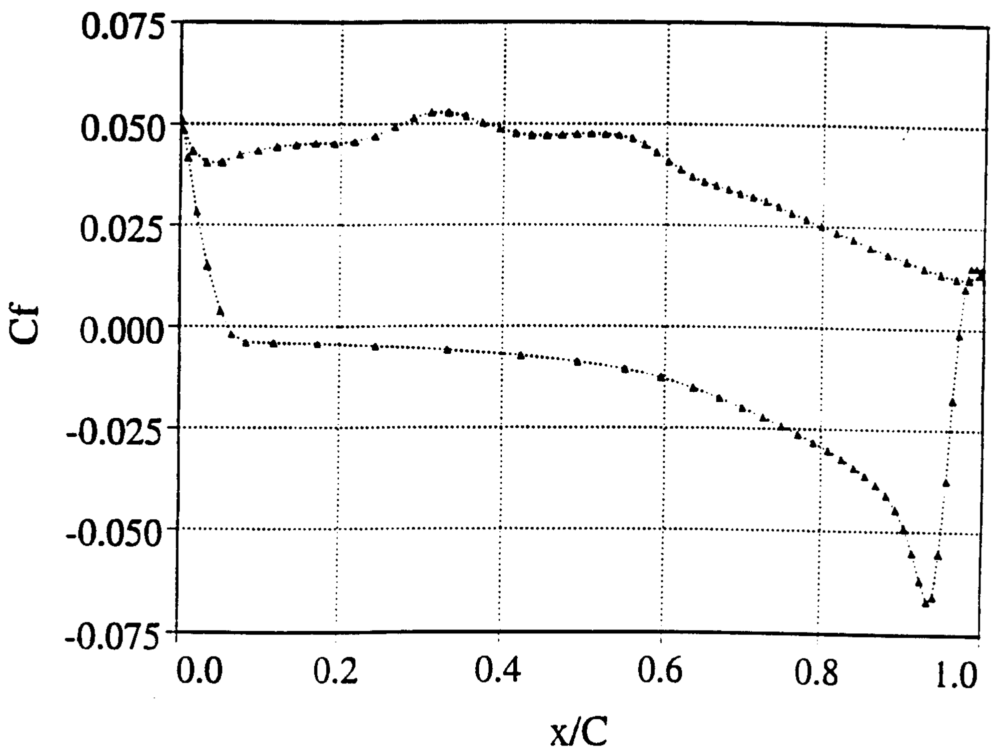

Figure 6. Skin Friction Distribution, Chord R_e =2000K, H Grid =99x51, O Grid=99x29, Chord/Pitch=1.075

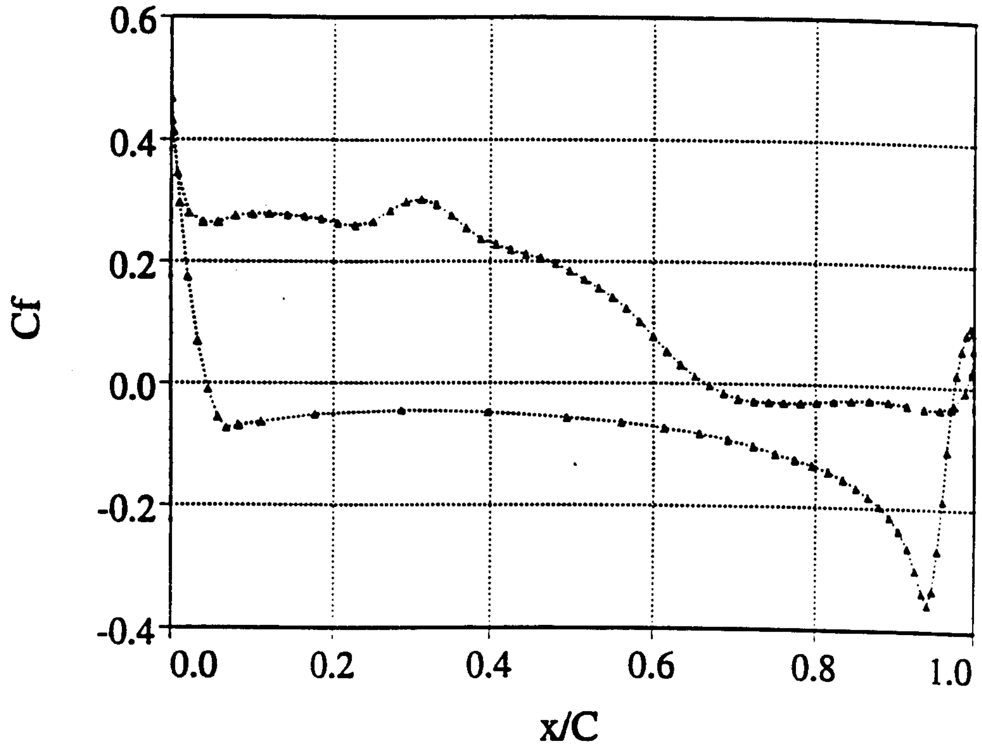

Figure 7. Skin Friction Distribution, Chord R_e =50K, H Grid =99x51, O Grid=99x29, Chord/Pitch=0.84

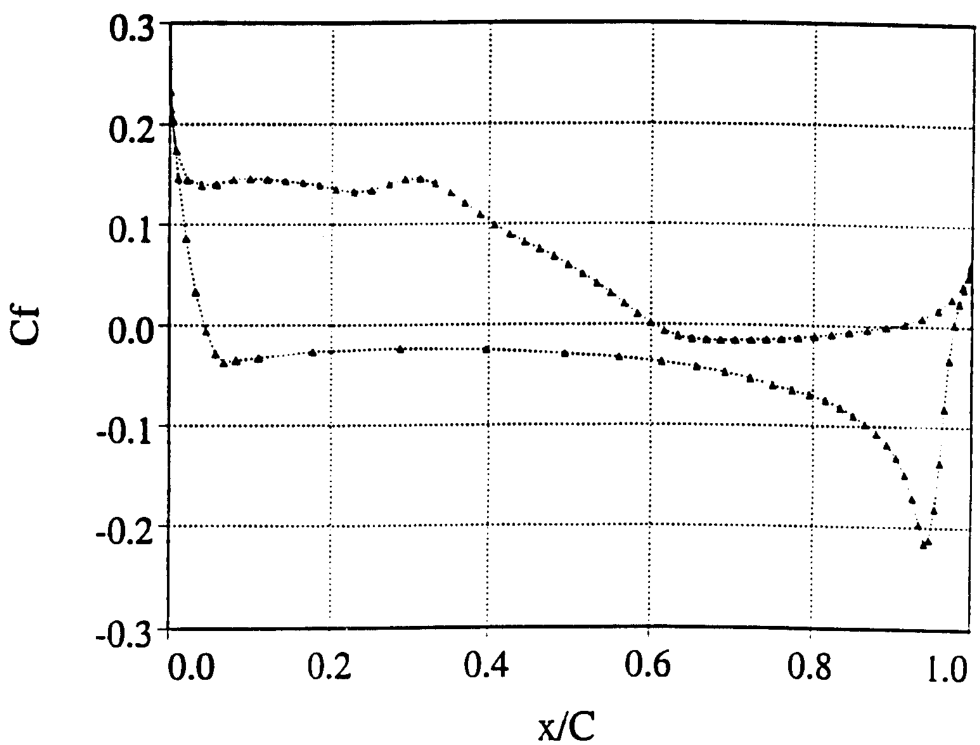

Figure 8. Skin Friction Distribution, Chord R_e =100K, H Grid =99x51, O Grid=99x29, Chord/Pitch=0.84

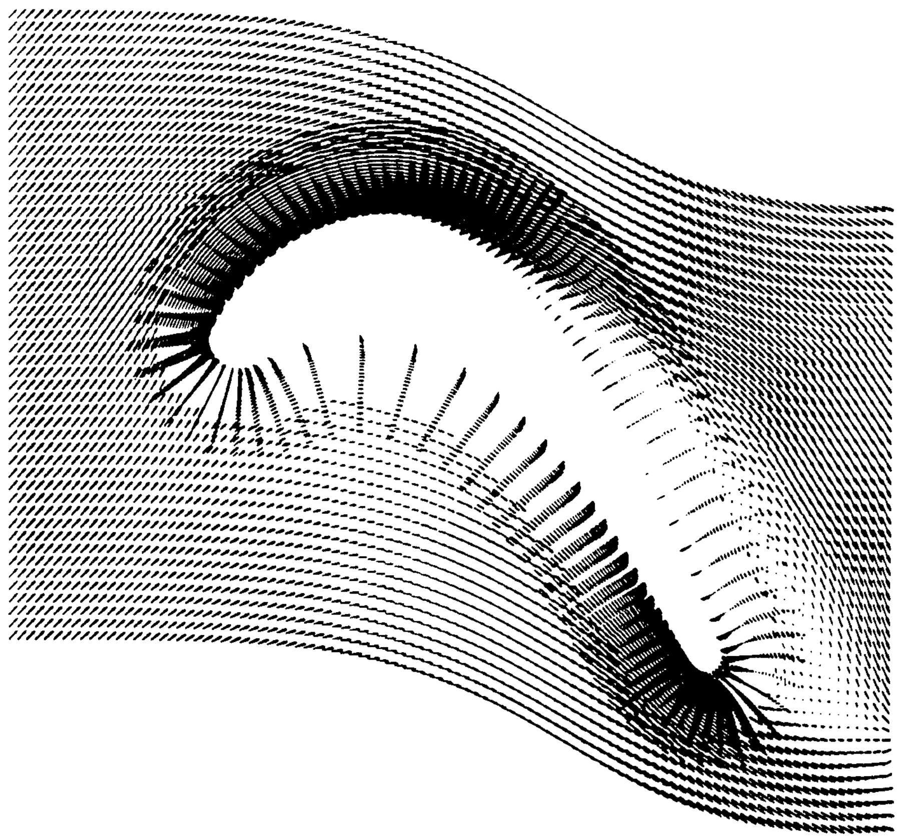

Figure 9. Velocity Vector Profiles, Chord R_e =441K, H Grid =99x51, O Grid=99x29, Chord/Pitch=0.84

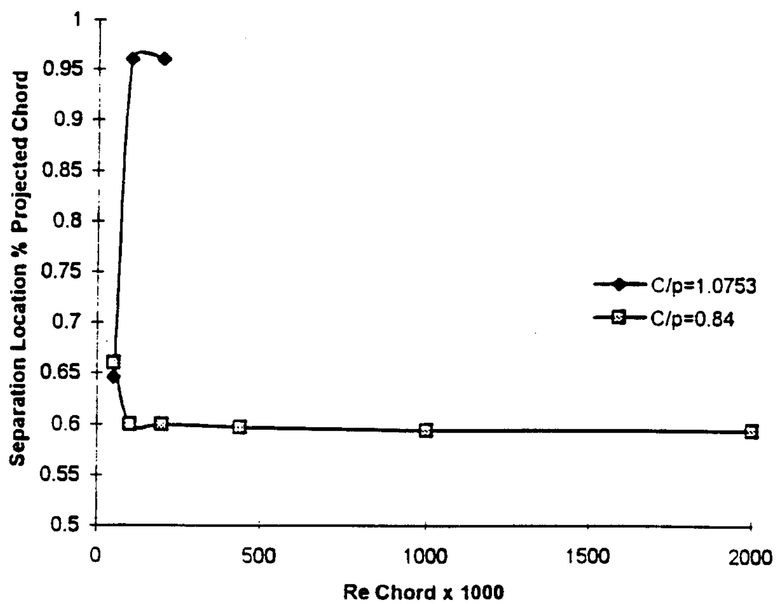

Figure 10. Separation Location in % Projected Chord

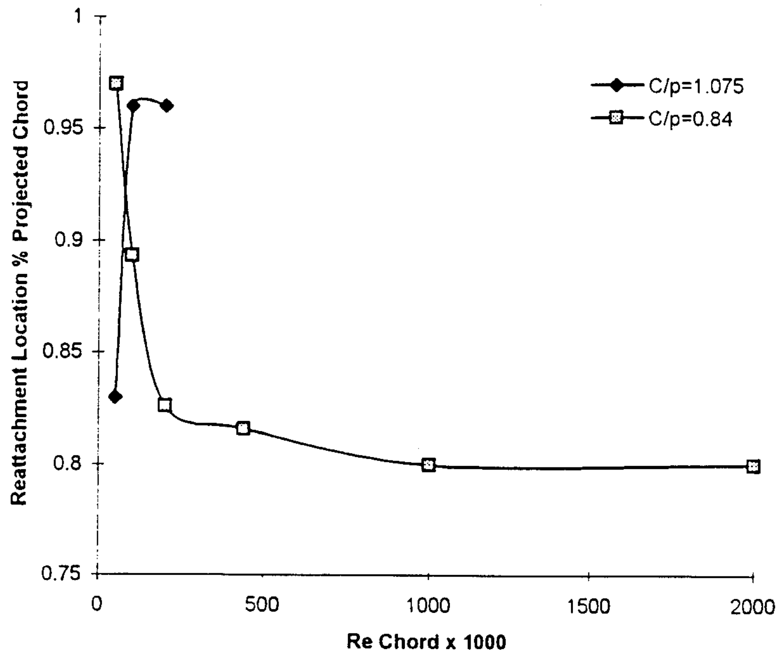

Figure 11. Reattachment Location in % Projected Chord

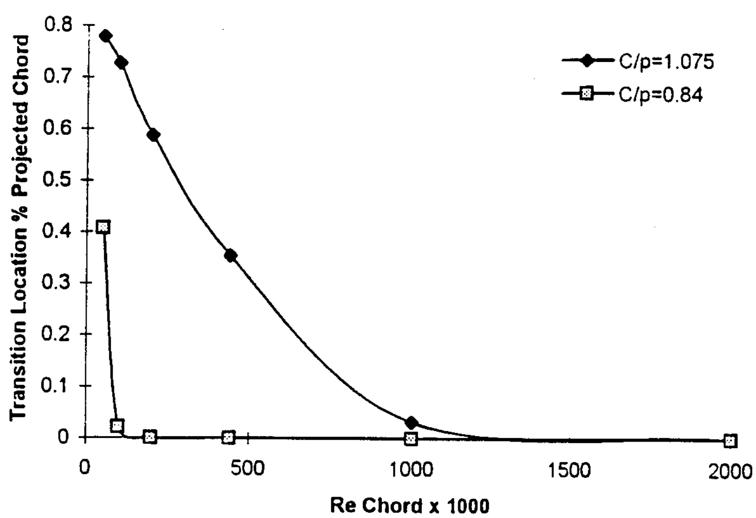

Figure 12. Transition Reynolds Number Dependence in % Projected Chord

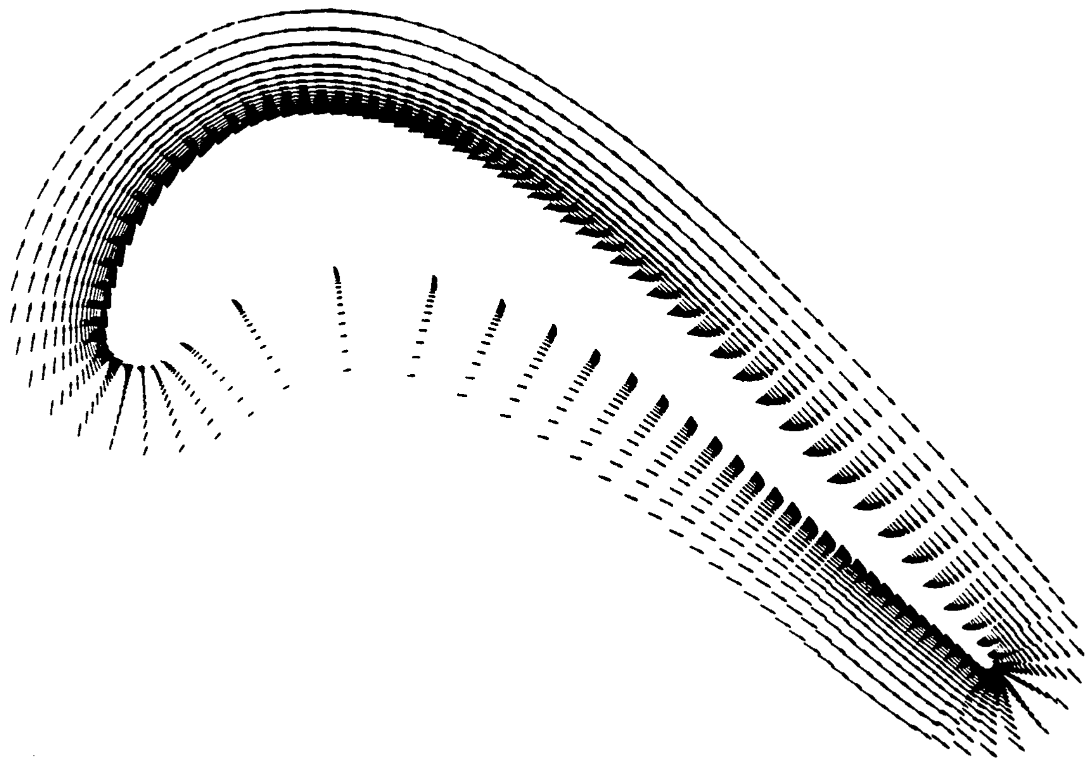

Figure 13. Vector Velocity Profile Thinned Blade, Chord R_e =50K, H Grid =99x51, O Grid=99x29, Chord/Pitch=0.84

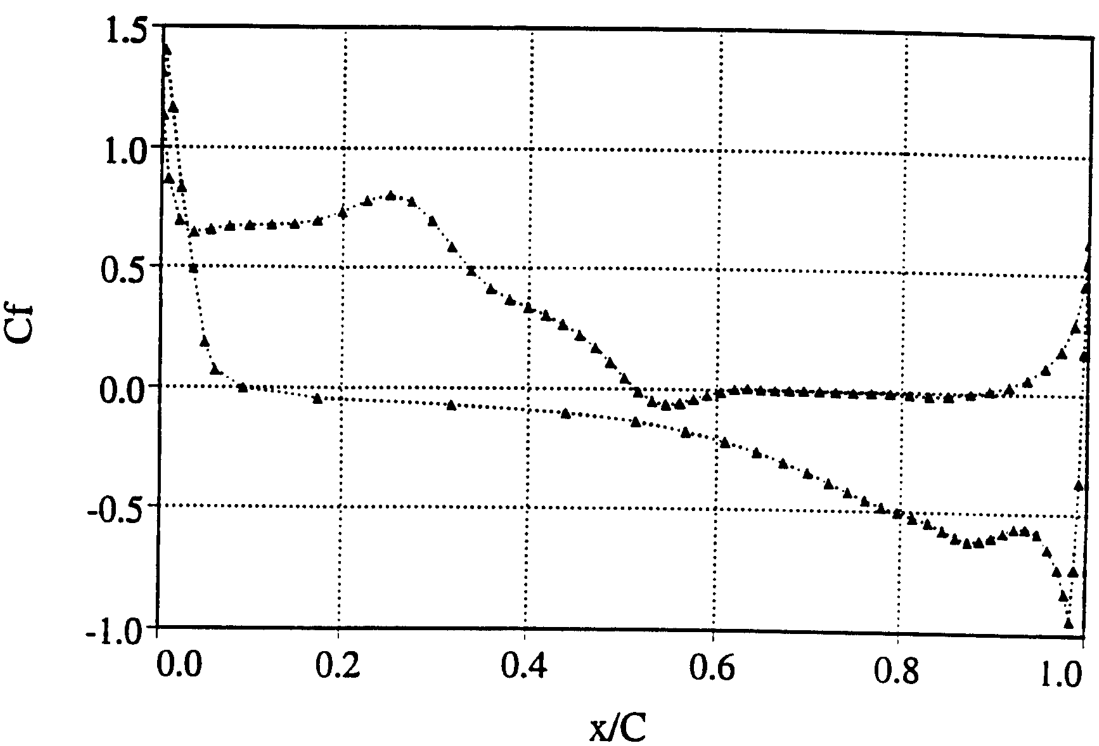

Figure 14. Skin Friction Coefficient Distribution Thinned Blade, Chord R_e=100K, H Grid =99x51, O Grid=99x29, Chord/Pitch=0.7857